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Sixth International Conference on Composite Materials
(ICCM-VI)

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Selected papers presented in five of the six sessions held at this meeting in London, UK, are discussed. These areas covered in the sessions these papers were given are: metal matrix composites, ceramic matrix composites, mechanical characterization, impact, and nondestructive testing.

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# SIXTH INTERNATIONAL CONFERENCE ON COMPOSITE MATERIALS (ICCM-VI)

The Sixth International Conference on Composite Materials (ICCM-VI) was held at the Imperial College of Science and Technology, London, UK. It was very well attended, with participation by over 800 scientists involved in various aspects of composites research and development. The technical program consisted of approximately 250 papers from 28 countries. Because of the large number of papers presented, six parallel sessions were held concurrently. The areas covered in these sessions included: manufacture, fibers, polymer matrices, metal matrix composites, ceramic matrix composites, mechanical characterization, fracture, fatigue, impact, durability, nondestructive evaluation, and structural analysis.

Of particular note was the large number of industrial companies now involved in developing aluminum composites reinforced with discontinuous particles or whiskers. The reason for the great interest in these materials is enhancement in stiffness, strength, erosion resistance, and low cost. Low ductility and poor fracture toughness, which had plagued them in the past, has been overcome as a result of processing improvements, in particular, the discovery that reinforcement particles are of great importance. Low-cost fabrication processes such as squeeze and rheocasting are among the processes being most avidly pursued.

Work in ceramic composites primarily involved understanding the relation between composite architecture and mechanical properties. Ceramic composites with metal-like toughness are now available. The realization of the importance of controlling interfacial properties is the key to achieving tough ceramic composites. Within the mechanics and structures communities, there was increased emphasis on the coupling between the microstructural aspects and global response of composites. In addition, the synergistic interactions between complex mechanical, thermal, and environmentally induced stress states resulting in material degradation and reduced life are being investigated. In view of the susceptibility of laminated structural composites to impact damage, experimental methods for the assessment of damage states and analytical methods for structural integrity analyses are being developed.

Within the constraints of the meeting's parallel sessions, we covered selected sessions of interest, those in the areas of metal matrix composites, ceramic matrix composites, mechanical characterization, impact, and nondestructive evaluation. Summaries are provided in the sections following.

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## Metal Matrix Composites Highlights

Research in metal composites, which has been underway since the early 1960's, was initially concentrated in high-performance materials with superalloy matrices and expensive boron or SiC fibers, an interest which is still being pursued for aerospace and advanced military applications. Current industrial work is focused primarily on lower cost metal matrix composites (MMC's) with aluminum and magnesium matrices reinforced with cheap, short fiber or particulate ceramics such as the type pioneered under US Navy programs in the mid-1970's. Indeed, most of the papers on MMC's presented at ICCM VI were concerned with such discontinuous reinforced aluminum composites. These materials are intended for applications approaching 500°C, and much effort is being expended on developing low-cost processes and improving material mechanical properties. At least three producers of SiC particulate-reinforced aluminum (Alcoa, DWA Composite Specialties Inc., and Advanced Composites, Inc.) have been able to overcome the low ductility and poor fracture toughness which were weaknesses in earlier composites of this type.

The subject matter of most of the papers on MMC's at this conference involved understanding processing-structure-property relationships from either an experimental, theoretical, or a combined theoretical/experimental standpoint. There were about 20 papers dealing with mechanical properties of MMC's. S.J. Harris and T.E. Wilks, University of Nottingham, UK, described the tensile and fatigue properties of two aluminum alloys reinforced with short "Saffil" alumina fibers, fabricated by infiltration of a fiber preform using a squeeze casting operation. The composites showed an increase in both elastic modulus (greater than 20 percent) and in the level of matrix work hardening. For a 99.85-percent Al matrix, both tensile, and fatigue strengths were increased by the presence during fatigue of four-point bend samples. Such crack initiation was attributed to large strain concentrations due to matrix deformation which led to interface debonding. Propagation by linking of these short cracks was then observed.

The effect of SiC particle size on the fracture behavior of SiCp/Al composites was reported by Y. Florm and R.J. Arsenault, University of Maryland. Their tensile test data show that the Young's modulus is independent of

SiC particle size. Yield and ultimate strengths decrease, and strain to fracture increases as SiC particle size increases. Fracture behavior of SiCp/Al has features of brittle and ductile mechanisms. The fracture process is matrix-controlled up to SiC particle sizes of 20 micrometers, above which fracture of the SiC begins to dominate. The matrix is influenced by the residual hydrostatic tension and high density of dislocations generated at SiC/Al interfaces due to differences in thermal expansion between the SiC and Al. Although crack initiation fracture toughness is SiC particle size-independent, crack growth fracture toughness increases with SiC particle size. The latter factor is attributed to an increase in the size of the plastic zone at a crack tip which results in increased dissipation of plastic energy during crack propagation.

In a similar study, W.H. Hunt, O. Richmond, and R.D. Young (Alcoa Laboratories) investigated the effect of SiC particle clustering in SiCp/Al composites. A quantitative metallographic approach was employed to quantify the degree of particle clustering as a function of the experimental variables of Al/SiC particle size ratio and nominal SiC particle volume fraction. This study showed that particle clustering may play a significant role in the fracture initiation process in high-volume fraction materials. The authors pointed out that existing void nucleation models such as those of Evensen and Verk or of Brown and Embury do not predict material interest. A possible explanation, that void growth and coalescence become less dependent on the mode of void nucleation for high-volume fraction materials is a subject for future research.

A. Kohyama, H. Tezuka, and N. Igata reported on the effects of subjecting multifilament-yarn SiC fiber (Nicalon)-reinforced aluminum to neutron irradiation ($10^{23}$-$10^{24}$n/m$^2$). Such materials are thought to be potential candidates for nuclear reactors because of their low radiation-induced radioactivity characteristics. Both microstructural and mechanical property changes were reported. After high-temperature irradiation (723 K), increases in both Young's modulus and composite tensile strength were observed. The authors suggest that the neutron damage could induce heterogeneous nucleation of SiC crystals in the largely amorphous Nicalon which induces enhancement modulus hardening.

In work intended to provide better understanding of the crucial fiber-matrix interface, S.P. Rawal, L.F. Allard, and M.S. Misra (Martin Marietta Denver Aerospace) reported upon a detailed transmission electron microscopy investigation of interfaces in Gr/Al and Gr/Mg composites. Three different precipitate morphologies (blocky, lath shaped, and fine cuboidal) of similar chemical composition were identified near Gr/Al interfaces, and two (lamellar and spherical) of Mg17Al12 near Gr/Mg interfaces. Both Gr/Mg and Gr/Al exhibited a high density of dislocations, which was attributed to differential contraction in the fiber and matrix during cooling from fabrication. Dislocation substructure in diffusion-bonded Gr/Mg was primarily planar, whereas dense dislocation tangles were observed in diffusion-bonded Gr/Al and cast Gr/Mg. High damping values measured in these materials were attributed to the large dislocation density and associated residual stress state in these composites.

Nearly half of the papers concerning metal composites involved various methods for solidification processing such as squeeze-casting or rheocasting, perhaps the most inexpensive of processing techniques. F. Girot, et al. (University de Bordeaux, France) reported on the processing and properties of composites of Al reinforced with SiC whiskers or chopped fibers fabricated by compocasting, a slurry-casting technique. Mechanical test data showed an increase in stiffness, hardness, and dynamic toughness as compared to unreinforced aluminum. The authors also reported a decrease in ductility, impact resistance, and strength for the composites. Although high-temperature (350°C) strength for the composite was superior to unreinforced aluminum, no corresponding improvement was observed at 20°C. The poor room-temperature behavior was attributed to poor fiber distribution.

Two papers were presented by Massachussetts Institute of Technology scientists – papers by J.A. Cornie et al. and L.J. Masur et al. – on theoretical aspects of cast metal composites. The first, on wetting, fluidity, and solidification, described the fundamentals of wetting behavior at the interface between infiltrating and solidifying molten metal and the ceramic reinforcement, fluid flow with accompanying solidification and macrosegration, and solidification in the presence of a ceramic reinforcement. In the second paper, concerned with pressure casting of fiber-reinforced metals, an apparatus was described which allows continuous measurement of the position of the metal as it infiltrates a fiber preform. Measurement of the permeability and infiltration length indicated a strong dependence on fiber volume fraction and fiber temperature, but a weaker dependence upon metal temperature. It was shown that the presence of metal superheat results in remelting of solid metal at the infiltration front some distance into the composite. The authors presented an analytical expression describing a lower bound estimate of this remelt distance. Results of permeability measurements indicate a solidification mechanism that differs from the uniform fiber coating mechanism proposed by other investigators. In the present work, the fine network of fibers acts as a "filter" to retain solid metal dendrites while the liquid metal flows past to form more solid metal downstream as it encounters new cold fibers. Behind the solidification front there exists a region where the metal matrix contains a uniform volume fraction of solid and where the temperature is constant at Tm, assuming equilibrium at the liquid/solid interface.

That little work is being conducted in corrosion and environmental effects in metal matrix composites was emphasized by the fact that only a single paper on corrosion in metal composites was presented. Renjie Wu and Wei-

dong Cai (Shanghai Jiao Tong University, China) presented the results of a study on the effects of moisture and heat on Gr/Al composites. Weight gains in the composites were attributed to the hydrolysis of $Al_4C_3$ at fiber/matrix interfaces to form $Al(OH)_3$. Metallographic investigation showed extensive crevice formation and corrosion-product wedging.

## Ceramic Matrix Composite Highlights

The main disadvantage of ceramics is low toughness. Consequently, development of high toughness and high work of fracture in brittle matrix composites has been the goal of most investigators. The most successful of these has been through the use of composite techniques, either with short fiber or whisker reinforcements, or with continuous reinforcements. Through the use of continuous fiber reinforcements, ceramics have been demonstrated with "metal-like" toughness values. As in the case of other classes of high-performance composites, there is much effort in developing cost effective processing methods and in understanding mechanical mechanisms. In fabricating ceramic composites with continuous reinforcements, there is an almost universal effort in protecting the fiber during consolidation or in using methods which avoid fiber damage. R. Lundberg et al., Swedish Institute for Silicate Research, reported a potentially inexpensive technique for fabrication of SiC fiber-reinforced $Si_3N_4$. The method involved slip infiltration of $Si_3N_4$ fibers with a slurry consisting of Si, $Si_3N_4$, and $Y_2O_3$ (as a sintering aid). The slurry is reaction sintered to form a $Si_3N_4$ matrix. The role of the $Si_3N_4$ particulate in the slurry is that of a dispersant to enable the Si to reach submicron size during melting, to prevent sintering during nitridation by keeping Si particles apart, and acting as a heat sink during thermal nitridation reaction. No reactions was observed between fiber and matrix during fabrication. Bend tests showed a nonbrittle fracture mode with fiber debonding and pullout resulting in increased fracture toughness as compared with unreinforced reaction-bonded silicon nitride.

The use of natural fibers to reinforce brittle matrices was described in a paper by A.C. Khazonchi et al. (Bhopal Regional Research Laboratory, India). Sisal fiber, a lignocellulosic fiber which grows all over the world, was used as a replacement for asbestos in cement sheet. The surface of the fibers was modified by alkali in order to promote strong bonding with the matrix through the creation of mechanical locking sites. The authors reported on the structure of the sisal fibers and the special problems (fungal and termite attack) which are associated with the use of such natural organic reinforcements. Composites were fabricated by mixing chopped sisal fibers with sand-cement slurry and casting in corrugated molds. It was determined that mechanical properties of the sisal fiber-reinforced cement were adequate for roofing purposes. The sheet is superior to asbestos-cement by not being carcenogenic.

There were several papers on high rate effects in ceramic matrix composites. T. Macke et al. (Université de Bordeaux, France) investigated the manner in which the properties of the fiber and the matrix modify the impact response as a function of composite architecture in ceramic composites. In their experiments they included two- and three-dimensional (2-D and 3-D) composites with low and high modulus fibers and the effect of interposing a thin, compliant interfacial layer. They observed that low modulus fibers enhanced the compliance of the fibrous structure and consequently the damage absorption ability of the matrix prior to fiber rupture in both the 2-D and 3-D architectures. The impact results were analyzed based on a dynamic analysis. Dynamic toughnesses were derived from fracture initiation, and dynamic crack growth resistance curves used to determine strain energy release rates. Significant differences were observed in SiC/SiC composites with and without the presence of a compliant interfacial layer. The improvement in dynamic toughness and rupture work while maintaining high rigidity for the SiC/SiC with the compliant interface was attributed to the protection of the fibers from notch effects induced by microcracks in the matrix.

K. Kageyana and T.-W Chou (University of Delaware, Newark) used the Distributed Dislocation Method to analyze toughening mechanisms of crack deflection and fiber pullout in short-fiber-reinforced ceramic matrix composites. In their analysis, which used a stress intensity factor approach, the effects of closure force, load transfer, and crack impediment were considered. The fracture criterion used was of a mixed mode and contained both I and II loading modes. A statistical distribution of the number of fibers pulled out on the fracture surface was applied to the model of toughening. The combined effects of crack deflection and fiber pullout were used to predict the failure probability in short-fiber-reinforced ceramic composites.

M. Bouquet et al. (Université de Bordeaux, France) presented a combined theoretical/experimental paper in which 2-D and 3-D ceramic composites were considered as quasi-elastic materials with regard to composite mechanical behavior. 2-D and 3-D SiC/SiC composites were tested under tension, bending, and compressive loading. From the results of the testing and considering these composites as quasi-elastic materials, the mechanical behavior, as demonstrated by their stress-strain curves, could be depicted with a simple model based on the occurrence of frictional phenomena between the fibers and the microcracked matrix.

## Mechanical Characterization Highlights

The sessions on mechanical characterization included papers dealing with test methods for fiber-reinforced composite materials, with the emphasis on tensile and compressive testing, together with modeling of stiff-

ness properties and failure in the linear and nonlinear range. Some contributions to this area are described in the following.

The tensile behavior of hybrid glass/carbon/epoxy quasi-isotropic laminates was discussed in a paper by G. Kretsis, F.L. Matthews, J. Morton, and G.A.O. Davies of the Imperial College of Science and Technology, London, UK. The authors showed that, in general, stiffness and strength decreased as the amount of glass in the laminate was increased, while the opposite was true for the strain to failure. Their computational model for the nonlinear stress-strain behavior of the laminate, together with the Tsai-Hill failure criterion, was shown to predict the measured experimental tensile strength satisfactorily.

Kink band formation in unidirectional composites subjected to compression was discussed in a paper by H.T. Hahn (Pennsylvania State University, University Park). The kinematics of kink band formation was described in terms of a deformation tensor, and equilibrium equations were applied to relate the compression load to the deformation of fibers. Kink bands were assumed to be the result of in-phase bending failure of fibers. The author's analysis indicated a substantial amount of plastic shear deformation occurring within kink bands.

A one-parameter orthotropic plasticity model to describe the nonlinear behavior of undirectional composites was presented by C.T. Sun (Purdue University, Lafayette, Indiana). This model was based on an orthotropic elastic-plastic formulation for the nonlinear behavior of boron/aluminum composites by Kenoga et al., which involved three parameters, determined experimentally. The assumption that the stress-strain relation is basically linear elastic in the fiber direction enabled the authors to reduce the number of parameters. This model was shown to predict accurately the experimentally measured off-axis deformation characteristics of boron/aluminum and graphite/epoxy composites.

The compression strength of aligned carbon-fiber-reinforced thermoplastic laminates was discussed in a paper by the UK's R.J. Lee (Harwell Laboratory) and A.S. Trevett (University of Bath). the compression behavior of reinforced thermoplastic laminates was compared with that of two epoxide resin systems produced by compression molding and filament winding. Unidirectional carbon/PEEK composites were shown to have similar compression strength to the epoxide composites at room temperature, but a greater strength reduction at elevated temperatures.

The difficulties associated with the mechanical testing of composites reinforced with Kevlar aramid fibers were discussed in a paper by M.W. Wardle of DuPont and D.A. Steenkamer of the University of Delaware. The authors provided special techniques for the preparation of test specimens and modifications necessary of standard test geometries in the tension, compression, shear, and flexure testing of these composites.

## Impact Damage Highlights

The sessions on impact damage included a plenary paper surveying impact damage in composites, and contributed papers in the areas of transverse impact testing using a Hopkinson pressure-bar technique, spall fracture in thermoset and thermoplastic composites, and energy absorption by cylindrical tubes subjected to axial crushing.

A plenary paper by G. Dorey (Royal Aircraft Establishment, Farnborough, UK) provided results from a series of impact tests on composites of carbon, glass, and polymeric fibers in either thermosetting or thermoplastic resins. The relationships between fracture characteristics of the various systems and the fiber and matrix properties were discussed. The dependence of the extent of damage on the velocity, energy, and the shape of the impacting projectile, and on the dynamic response of the composite specimen was delineated. In light of today's relatively low design limits for composite structures as compared with design limits for metal structures, the author reiterated the need for improved understanding of the failure processes of composites before they can be used with greater efficiency.

The transverse impact testing of composite laminates using a Hopkinson-type pressure-bar technique was discussed by J. Harding and R.K.Y. Li (University of Oxford, UK). Results were presented for low-velocity impacts on plain-weave reinforced epoxy laminates with either all-carbon plies or a hybrid combination of carbon plies and glass plies. These suggest that when woven glass plies are added to an all-carbon laminate, the principal energy absorbing mechanism for transverse impact loading changes from one associated with fiber fracture to one associated with delamination.

The nature of spall fracture, or through-the-thickness tensile impact fracture, in composite laminates with thermosetting and thermoplastic matrices, was discussed in a paper by N. Takeda, H. Komatsu, and K. Takahshi (Kyoto University, Japan). They used an exploding foil technique to accelerate thin flyer plates towards the composite laminates to generate spall fractures. For thermosetting polyester composites, different fiber surface treatments were applied to study the effects of interfacial strengths on the impact fracture thereshold conditions and spall mechanisms. The static interfacial strength was correlated with the threshold condition for spall fracture initiation. The principal spall fracture mechanism was identified to be brittle debonding between fibers and resin. For thermoplastic polypropylene composites, on the other hand, plastic deformation was shown to play an important role in spall fractures by absorbing considerable impact energy.

An investigation into the energy absorption capacity of cylindrical glass-cloth/epoxy tubes subjected to axial crushing was discussed in a paper by D. Hull and A.H. Fairfull (University of Cambridge, UK). For tubes suffi-

ciently short to prevent Euler buckling, specific energy absorption was shown to vary only with cross-sectional dimensions. Thus, the authors were able to display the results of their investigations in the form of a failure map, with three types of crushing behavior in different regimes.

The response of sandwich composite specimens to low-velocity impact damage was discussed in a paper by T. Gottesman, M. Bass, and A. Samuel (Israel Aircraft Industries, Lod, Israel). The damage pattern consists of delaminations through the thickness of the skin, accompanied by fiber breakage in the upper layers. A simple analytic model was used to assess strength reduction due to impact-induced damage. The predicted strengths were consistently conservative when compared with experimental data.

## Nondestructive Testing Highlights

In the area of nondestructive testing and evaluation (NDE) of composites, there were presentations dealing with several techniques based on acoustic emission, thermal waves, and Raman spectroscopy. Some of the highlights of these sessions are summarized below.

An overview of the nondestructive evaluation of composite structures was provided in a plenary paper by D.E.W. Stone (Royal Aircraft Establishment, Farnborough, UK). His focus was on continuous fiber composites used in aerospace structures, and laboratory methods of inspection were reviewed. He emphasized the versatility of the range of techniques based on ultrasonics, and the need for complementary methods such as penetrant-enhanced x-radiography – if detailed characterization is necessary. Stone summarized the techniques appropriate for production inspection and in-service inspection.

The use of acoustic emission for the nondestructive evaluation of graphite-epoxy composites was discussed by M. Suzuki, et al., Kyoto Institute of Technology, Japan. By studying model systems of unidirectional and angle-ply laminates, identifying the dominant modes of failure, and conducting acoustic emission frequency spectrum analysis, these authors identified the frequency domain features characteristic of matrix fracture, fiber-matrix debonding, fiber fracture, and friction due to slip at the interface.

Another paper on acoustic emission, this one by K. Ono, M. Ohtsu, and S. Jensen (University of California, Los Angeles), described an experimental investigation which used advanced digital signal processing and pattern recognition analysis. Discrimination between the different failure modes was accomplished on the basis of peak amplitude and event duration of observed vectors in the pattern recognition analysis. The pattern classification was shown to identify five distinct types of signals, and correlations were made with different failure modes.

The use of photothermal wave analysis for noncontacting nondestructive evaluation (NDE) of composites was discussed by B. Rief, G. Busse, and P. Eyerer (University of Stuttgart, West Germany). They showed that this technique could be used to estimate the fiber content in the composite with a very high degree of accuracy (to within 1 percent). In addition, they demonstrated the capability of this technique to detect near-surface inhomogeneities in the form of cracks, delaminations, and insertions occurring at depths up to 0.125 mm.

A paper by S.L. Toh, F.S. Chou, H.M. Chang, and C.J. Toy (National University of Singapore) described an experimental program which explored the use of the optical method of shearography for the detection and sizing of subsurface flaws in composites. Shearography is an interferometric method which provides whole-field observation of derivatives of small surface displacements and hence, strain. The simulated disbonds or delaminations were air pockets of different sizes introduced at different layers within the composite plates during fabrication. Two speckle patterns were obtained under two different conditions: one with the plate at atmospheric pressure and the other with the plate under partial vacuum in a vacuum chamber. These patterns were processed to obtain the shearograms which were examined and the fringe densities correlated with defect size and defect depth.

A review paper on the use of Raman spectroscopy for NDE of composites was presented by J. Summerscales (Royal Naval Engineering College, Plymouth, UK). The Raman effect is a phenomenon involved in the scattering of light as it passes through a material, such that it undergoes a change in frequency and a random alteration in phase. The use of a laser beam which provides a highly collimated, small-diameter beam of intense, coherent, polarized and monochromatic radiation, has enabled the exploitation of the phenomenon for the nondestructive evaluation and chemical analysis of microscopic samples with a spatial resolution of one micron. Potential areas for use of this technique include: the degree of cure of epoxy resins, the degree of graphitization of PAN-based carbon fibers, and characterization of the surface of carbon and graphite fibers.

The use of this technique for the in-situ measurement of the distribution of strains along individual fibers in polymer matrix composites was discussed in a paper by I.M. Robinson, et al. (University of Manchester, UK). They used an optomechanical strain gauge to study axial strain variations along the length of a fiber embedded in an epoxy matrix, at different levels of applied matrix strain. The strain distributions were shown to be qualitatively similar to those predicted by the widely used approximate shear-lag model due to Cox, and were in quantitative agreement with detailed finite difference calculations. The critical length of the fibers was measured directly, and was shown to decrease with increasing fiber volume fraction. The ability of this technique to measure the intensification of strains along a fiber in the neighborhood of a blunt crack was also demonstrated.

## Summary

The Sixth International Conference on Composite Materials provided a forum for the exchange of information on all aspects of composites by the international composites research and development community. It brought together workers in diverse disciplines (chemistry, material science, mechanics, structures, manufacturing, design engineering, nondestructive testing), all with a common interest, to assess the latest advances in composites.